

Evaluation of the performance of combined cooling, heating, and power systems with dual power generation units



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HIGHLIGHTS

- We investigate benefits from using combined cooling, heating, and power systems.
- A dual power generation unit configuration is considered for CCHP and CHP.
- Spark spreads for cost, energy, and emissions correlate with potential savings.
- Thermal difference parameter helps to explain variations in potential savings.
- Carbon credits may increase cost savings where emissions savings are possible.

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ABSTRACT

The benefits of using a combined cooling, heating, and power system with dual power generation units (D-CCHP) is examined in nine different U.S. locations. One power generation unit (PGU) is operated at base load while the other is operated following the electric load. The waste heat from both PGUs is used for heating and for cooling via an absorption chiller. The D-CCHP configuration is studied for a restaurant benchmark building, and its performance is quantified in terms of operational cost, primary energy consumption (PEC), and carbon dioxide emissions (CDE). Cost spark spread, PEC spark spread, and CDE spark spread are examined as performance indicators for the D-CCHP system. D-CCHP system performance correlates well with spark spreads, with higher spark spreads signifying greater savings through implementation of a D-CCHP system. A new parameter, thermal difference, is introduced to investigate the relative performance of a D-CCHP system compared to a dual PGU combined heat and power system (D-CHP). Thermal difference, together with spark spread, can explain the variation in savings of a D-CCHP system over a D-CHP system for each location. The effect of carbon credits on operational cost savings with respect to the reference case is shown for selected locations.

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1. Introduction

Combined heat and power (CHP), or cogeneration, and combined cooling, heating, and power (CCHP), or trigeneration, systems are used to produce electricity on-site while making use of waste heat expelled from the power generation unit (PGU). The waste heat recovered from the PGU can be used to help meet building thermal demands. Typically, CHP and CCHP systems employ a single PGU operating in one of three modes: following the electric load (FEL), following the thermal load (FTL), or base-loaded (BL). Comprehensive reviews of CHP and CCHP systems have been prepared by Mago et al. (2009), Al-Sulaiman et al. (2011), and Wu and Wang (2006). Recently,

Knizley and Mago (2012a, 2012b) proposed a CHP configuration where two PGUs operate simultaneously (D-CHP), with one PGU delivering power at a constant base load and the other PGU operated FEL. CHP and CCHP systems provide a potential for cost, primary energy consumption (PEC), and emissions savings over a traditional separate heating and power (SHP) configuration. Cho et al. (2009) examine CCHP systems on the bases of operating cost, PEC, and carbon dioxide emissions (CDE), using minimization functions to optimize the system operation based on each parameter. They determined that each optimization mode presents independent results. In other words, optimizing the CCHP system on the basis of cost minimization does not imply that PEC or CDE will also be minimized. Fumo and Chamra (2010) studied a CCHP system on the basis of PEC to define CCHP system operation conditions that can guarantee PEC savings. They determined that PEC savings cannot be guaranteed at all times, but that an analysis based on PEC can help

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Nomenclature

CHP	combined heat and power	E_{grid}	auxiliary electricity provided by grid
CCHP	combined cooling, heating, and power	$\eta_{\text{pgu1}}, \eta_{\text{pgu2}}$	respective efficiencies of PGU1 and PGU2
PGU	power generation unit	$F_{\text{pgu1}}, F_{\text{pgu2}}$	respective fuel energy requirement of PGU1 and PGU2
FEL	following the electric load	$E_{\text{pgu2}}^{\text{max}}$	maximum electrical energy output capability of PGU2
FTL	following the thermal load	$E_{\text{pgu2}}^{\text{min}}$	minimum electrical energy output for PGU2 to operate
BL	base-loaded	$Q_{\text{rec,pgu1}}^{\text{max}}$	maximum heat that can be recovered from PGU1
D-CHP	dual-PGU CHP system configuration	$Q_{\text{rec,pgu2}}^{\text{max}}$	maximum heat that can be recovered from PGU2
SHP	separate heating and power	ξ	PGU energy loss factor
PEC	primary energy consumption	η_{hrs}	efficiency of heat recovery system
CDE	carbon dioxide emissions	F_{boiler}	fuel needed to operate boiler
HETS	hybrid electric-thermal load	η_{boiler}	boiler efficiency
D-CCHP	dual-PGU CCHP system configurations	F_{pgus}	combined fuel energy requirement from both PGUs
Q_b	building heating demand (hourly)	F_m	metered fuel consumption
E_b	building electric demand, CCHP (hourly)	E_m	metered electrical energy
E_{fac}	facility electric demand, SHP (hourly)	Cost_e	cost of electricity (\$/kW h)
E_{cool}	cooling electric demand (hourly)	Cost_f	cost of fuel (\$/kW h)
Q_{cool}	cooling thermal demand (hourly)	PECF_e	primary energy conversion factor (electricity)
F_{fac}	facility fuel energy requirement (hourly)	PECF_f	primary energy conversion factor (fuel)
η_h	heating system efficiency, SHP	CDEF_e	carbon dioxide emissions factor (electricity)
COP_{vc}	vapor compression system coefficient of performance, SHP	CDEF_f	carbon dioxide emissions factor (fuel)
Q_{req}	thermal load required to meet building demand, CCHP	$\text{OpCost}_{\text{DCCHP}}$	operational cost of D-CCHP system
$Q_{\text{req,heat}}$	thermal load required to meet building heating demand, CCHP	$\text{OpCost}_{\text{ref}}$	operational cost of SHP system
$Q_{\text{req,cool}}$	thermal load required to meet building cooling demand, CCHP	$\text{PEC}_{\text{DCCHP}}$	PEC of D-CCHP system
$\eta_{h,\text{CCHP}}$	efficiency of heating coil, CCHP	PEC_{ref}	PEC of SHP system
$\text{COP}_{\text{chill}}$	chiller coefficient of performance, CCHP	$\text{CDE}_{\text{DCCHP}}$	CDE of D-CCHP system
$E_{\text{pgu1}}, E_{\text{pgu2}}$	respective electrical energy output of PGU1 and PGU2	CDE_{ref}	CDE of SHP system
E_{pgus}	combined electrical output from both PGUs	ΔCDE	CDE difference between SHP and D-CCHP
$Q_{\text{rec,pgu1}}$	heat recovered from PGU1	$\text{OpCost}_{\text{DCCHP}}^{\text{CC}}$	operational cost of D-CCHP system with carbon credits considered
$Q_{\text{rec,pgu2}}$	heat recovered from PGU2	$\text{OpCost}_{\text{savings}}$	operational cost savings of D-CCHP over SHP
Q_{rec}	total heat recovered from combined PGUs	$\text{PEC}_{\text{savings}}$	PEC savings of D-CCHP over SHP
Q_{boiler}	auxiliary heat provided by boiler	$\text{CDE}_{\text{savings}}$	CDE savings of D-CCHP over SHP
		Q_{thermal}	total thermal load required for building, CCHP
		R_{cool}	ratio of cooling load to total thermal requirement, CCHP
		R_{heat}	ratio of heating load to total thermal requirement, CCHP
		TD	thermal difference

determine operational strategies that yield the smallest amount of undesired PEC. From these authors, we note that, even if a CCHP system does not prove beneficial in terms of operational cost savings, it can still be worthwhile to examine the system with regard to PEC savings and CDE savings.

Kong et al. (2004) also explored the economic impact of a CCHP configuration in which the PGU is considered to be a Stirling engine. They focused on energy savings and economic feasibility in terms of cost and payback to conclude that the natural gas-based Stirling engine-driven CCHP system can save more than 33% of PEC as compared to a conventional, SHP system. They also noted that the performance of the chiller used in CCHP has a significant impact on the energetic efficiency of the CCHP system. Finally, they concluded that the price of natural gas, used to fuel the Stirling engine, was an important parameter influencing the economic performance of the CCHP system.

Several authors have analyzed CCHP and CHP systems operational strategies (Mago et al., 2009; Mago and Chamra, 2009; Espirito Santo, 2012; Fang et al., 2012a, 2012b; Wang et al., 2011; Smith et al., 2010; Liu et al., 2012; Jalalzadeh-Azar, 2004). Mago et al. (2009) compared CHP and CCHP systems operated FEL and FTL on the bases of PEC, operating cost, and CDE. For systems operated FEL, they determined that CCHP reduced the PEC, operating cost, and CDE compared to the CHP configuration for the four locations examined. The CCHP system

also outperformed the CHP system for most cases when operated FTL. In another study, Mago and Chamra (2009) looked at CCHP systems operated FEL and FTL to evaluate and optimize each strategy in terms of PEC, operating cost, and CDE. Additionally, they introduced a hybrid electric-thermal load operational scheme (HETS). They determined that optimization based on PEC was most favorable for the location examined and that HETS can be a viable alternative to a CCHP system operating FEL or FTL. Espirito Santo (2012) evaluated the performance of an IC engine-driven CCHP system on the basis of energy utilization factor, exergetic efficiency, and PEC savings for two different operational strategies. They found that the energy utilization factor can be between 65% and 81% for the given strategies, with efficiencies between 35% and 38.4%. Fang et al. (2012a, 2012b) proposed an integrated performance criterion to optimize CCHP operational strategies FEL or FTL on the bases of PEC, operating cost, and CDE. Wang et al. (2011) compared CCHP systems operating FEL and FTL against a SHP system on the bases of PEC savings, exergetic efficiencies, and CDE reduction. They determined that cooling load to electric demand and heating load to electric demand ratios can be indicative of CCHP performance. Smith et al. (2010) included model data uncertainty in the analysis of different CCHP operating strategies. They concluded that both FEL and FTL operations have minimal CDE and PEC uncertainties, with no uncertainty specified corresponding to CDE and PEC uncertainties, but that uncertainty involved in operating cost

is significant due to the uncertainties associated with electricity and natural gas prices. Liu et al. (2012) proposed an optimized operating strategy for a CCHP system with a hybrid chiller and compare that strategy to SHP, CCHP-FEL, and CCHP-FTL, and they determined that the proposed strategy is a feasible alternative to FEL, FTL, and SHP configurations. Jalalzadeh-Azar (2004) compared CHP-FEL and CHP-FTL to find that CHP-FTL presented a higher system efficiency and was less sensitive to seasonal load changes. Base-loaded CHP systems are implemented to allow the PGU to maintain constant efficiency and have been analyzed by Mago and Luck (2013), among others.

Knizley and Mago (2012a) proposed a CHP configuration that uses two PGUs in which one PGU is operated at base load and the other PGU is operated FEL. They determined that the D-CHP strategy can provide benefits in terms of operating cost, CDE, and PEC over CHP systems operating with a single strategy and single PGU. Mago et al. (in press) extended the D-CHP system analysis to include an FTL strategy in the analysis, as well as determine the effect of thermal storage on the D-CHP system performance. They found that, in general, a D-CHP system outperforms a single PGU CHP system on the bases of operational cost and CDE whether the second PGU is operated FEL or FTL. The addition of thermal storage to the system was found to increase the benefits of D-CHP.

From the literature, it is evident that CCHP and CHP systems can both yield savings in operational cost, carbon dioxide emissions, and primary energy consumption, and which system yields the greatest savings is dependent on climate, among other variables. Since some climate zones respond better to CCHP than CHP, and since D-CHP has been shown to perform comparably to or better than CHP (Knizley and Mago, 2012a, 2012b), the present work seeks to examine if D-CCHP can extend the benefits seen from D-CHP into a broader climate zone range. To do so, the D-CHP configuration is extended to examine a similar dual PGU configuration with the variation that the recovered heat from the PGUs is used to provide cooling to the facility using an absorption chiller (D-CCHP). The study of the proposed D-CCHP configuration has been motivated by the different climate conditions present in the US which will affect the building thermal load, especially the distribution of the yearly cooling load versus the yearly heating load. Therefore, the objectives of this paper are to evaluate the

performance of the D-CCHP system on the bases of operating cost, PEC, and CDE and to compare the D-CCHP system performance to that of the D-CHP system to determine under which circumstance the D-CCHP system is better than the D-CHP system or vice versa. Additionally, the effect of carbon credits on operational cost savings is also considered. Carbon credits up to \$30/t CO₂ (\$0.03/kg CO₂) are considered, within the range of previously proposed carbon tax prices for the U.S. (Castillo and Linn, 2011; Mori, 2012).

2. D-CCHP system model

The proposed D-CCHP system model employs two PGUs operating simultaneously to meet all or part of the building electric demand, heating demand, and cooling demand using an absorption chiller. A schematic of the D-CCHP system used in this paper is shown in Fig. 1.

The heating demand (Q_b), the cooling demand (Q_{cool}), and the electricity required by the building for everything except for cooling, can be found as

$$Q_b = F_{fac} \eta_h \quad (1)$$

$$Q_{cool} = COP_{vc} E_{cool} \quad (2)$$

$$E_b = E_{fac} - E_{cool} \quad (3)$$

where E_{fac} is the total electricity used for the facility in the SHP configuration, F_{fac} is the fuel energy used by the facility in the SHP configuration, E_{cool} is the electricity used for cooling in the SHP configuration, η_h is the efficiency of the building's SHP heating system and COP_{vc} is the vapor compression system coefficient of performance in the SHP configuration.

The thermal load required for the D-CCHP system components to meet the building demand (Q_{req}) is dependent on the efficiency of the heating system and COP of the absorption chiller used for D-CCHP system

$$Q_{req} = Q_{req,heat} + Q_{req,cool} \quad (4)$$

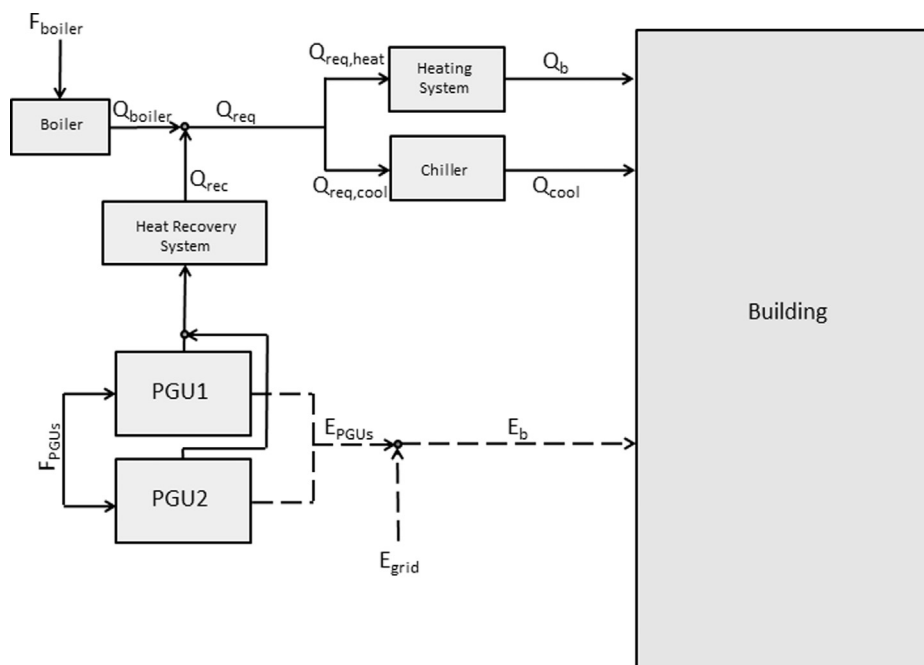


Fig. 1. Schematic of proposed D-CCHP configuration.

$$Q_{\text{req,heat}} = \frac{Q_b}{\eta_{h,\text{CCHP}}} \quad (5)$$

$$Q_{\text{req,cool}} = \frac{Q_{\text{cool}}}{\text{COP}_{\text{chill}}} \quad (6)$$

where $Q_{\text{req,heat}}$ is the heat required to satisfy all or part of the heating demand, $Q_{\text{req,cool}}$ is the heat required to satisfy all or part of the cooling demand, $\eta_{h,\text{CCHP}}$ is the efficiency of the heating coil, and $\text{COP}_{\text{chill}}$ is the coefficient of performance of the chiller.

The total electrical energy output from both PGU1 and PGU2 can be expressed as

$$E_{\text{PGUs}} = E_{\text{PGU1}} + E_{\text{PGU2}} \quad (7)$$

The heat recovered from the D-CCHP system, Q_{rec} , is the total amount of thermal energy that can be recovered from both PGU1 and PGU2, and

$$Q_{\text{rec}} = Q_{\text{rec,PGU1}} + Q_{\text{rec,PGU2}} \quad (8)$$

Any supplemental thermal or electrical energy needs are met by a boiler (Q_{boiler}) or purchased from the grid (E_{grid}) as follows

$$\begin{aligned} Q_{\text{boiler}} &= 0 \text{ if } Q_{\text{rec}} \geq Q_{\text{req}} \\ Q_{\text{boiler}} &= Q_{\text{req}} - Q_{\text{rec}} \text{ if } Q_{\text{rec}} < Q_{\text{req}} \end{aligned} \quad (9)$$

$$E_{\text{grid}} = E_b - E_{\text{PGUs}} \quad (10)$$

The equations modeling electrical output and heat recovered differ for each PGU, since the two PGUs are operated with differing strategies. PGU1 is base-loaded, and is therefore considered to maintain constant efficiency (η_{PGU1}), while the efficiency of PGU2 (η_{PGU2}) varies as it follows the electric load of the remaining electricity that is not provided by PGU1. The electrical capacity of each PGU, E_{PGU1} and E_{PGU2} , is chosen to maximize operational cost savings of the D-CCHP configuration.

For the base-loaded PGU, PGU1, the fuel energy required can be determined as

$$F_{\text{PGU1}} = \frac{E_{\text{PGU1}}}{\eta_{\text{PGU1}}} \quad (11)$$

and the fuel energy required for the PGU following the electric load, PGU2, is similarly defined

$$F_{\text{PGU2}} = \frac{E_{\text{PGU2}}}{\eta_{\text{PGU2}}} \quad (12)$$

where F_{PGU2} can be defined by

$$F_{\text{PGU2}} = aE_{\text{PGU2}} + bE_{\text{PGU2}}^{\text{max}} \quad (13)$$

where a and b are efficiency parameters for PGU2 can be determined by averaging coefficients to curve-fits of manufacturer's data for a small range of PGU sizes, and E_{PGU2} is the electrical output at its current operating state.

The maximum electric output from PGU2, $E_{\text{PGU2}}^{\text{max}}$, is the specified size of PGU2. PGU2 will not be operated when electrical output would be less than 25% of its maximum value in order to maintain reasonable efficiency.

$$E_{\text{PGU2}}^{\text{min}} = 0.25E_{\text{PGU2}}^{\text{max}} \quad (14)$$

The electrical output of PGU2 will vary according to

$$\begin{aligned} E_{\text{PGU2}} &= E_b - E_{\text{PGU1}} \text{ if } (E_b - E_{\text{PGU1}}) \leq E_{\text{PGU2}}^{\text{max}} \text{ and } (E_b - E_{\text{PGU1}}) \geq E_{\text{PGU2}}^{\text{min}} \\ E_{\text{PGU2}} &= E_{\text{PGU2}}^{\text{max}} \text{ if } (E_b - E_{\text{PGU1}}) > E_{\text{PGU2}}^{\text{max}} \\ E_{\text{PGU2}} &= 0 \text{ if } (E_b - E_{\text{PGU1}}) < E_{\text{PGU2}}^{\text{min}} \end{aligned} \quad (15)$$

The maximum thermal energy that can be recovered from each PGU is

$$\begin{aligned} Q_{\text{rec,PGU1}}^{\text{max}} &= \xi(F_{\text{PGU1}} - E_{\text{PGU1}})\eta_{\text{hrs}} \\ Q_{\text{rec,PGU2}}^{\text{max}} &= \xi(F_{\text{PGU2}} - E_{\text{PGU2}})\eta_{\text{hrs}} \end{aligned} \quad (16)$$

where ξ is an energy loss factor for the PGUs and η_{hrs} is the efficiency of the heat recovery system used for D-CCHP system.

The thermal energy recovered from each PGU when it is operating is

$$\begin{aligned} Q_{\text{rec,PGU1}} &= Q_{\text{req}} \text{ if } Q_{\text{req}} \leq Q_{\text{rec,PGU1}}^{\text{max}} \\ Q_{\text{rec,PGU1}} &= Q_{\text{rec,PGU1}}^{\text{max}} \text{ if } Q_{\text{req}} > Q_{\text{rec,PGU1}}^{\text{max}} \end{aligned} \quad (17)$$

$$\begin{aligned} Q_{\text{rec,PGU2}} &= Q_{\text{req}} - Q_{\text{rec,PGU1}} \text{ if } (Q_{\text{req}} - Q_{\text{rec,PGU1}}) \leq Q_{\text{rec,PGU2}}^{\text{max}} \\ Q_{\text{rec,PGU2}} &= Q_{\text{rec,PGU2}}^{\text{max}} \text{ if } (Q_{\text{req}} - Q_{\text{rec,PGU1}}) > Q_{\text{rec,PGU2}}^{\text{max}} \end{aligned} \quad (18)$$

Any fuel needed to operate the boiler can be found using boiler efficiency

$$F_{\text{boiler}} = \frac{Q_{\text{boiler}}}{\eta_{\text{boiler}}} \quad (19)$$

and the fuel required to operate both PGUs is

$$F_{\text{PGUs}} = F_{\text{PGU1}} + F_{\text{PGU2}} \quad (20)$$

The metered fuel and electricity, or that which must be purchased for the D-CCHP system operation, can therefore be expressed as

$$F_m = F_{\text{PGUs}} + F_{\text{boiler}} \quad (21)$$

$$E_m = E_{\text{grid}} \quad (22)$$

2.1. Performance parameters

The performance of the D-CCHP system can be measured in terms of operating cost, PEC, and CDE reductions over a reference case in which no CCHP or CHP system is implemented. The following equations yield operating cost, PEC, and CDE for the D-CCHP system and reference cases, respectively.

$$\text{OpCost}_{\text{DCCHP}} = E_m \text{Cost}_e + F_m \text{Cost}_f \quad (23)$$

$$\text{OpCost}_{\text{ref}} = E_{\text{fac}} \text{Cost}_e + F_{\text{fac}} \text{Cost}_f \quad (24)$$

$$\text{PEC}_{\text{DCCHP}} = E_m \text{PEC}_e + F_m \text{PEC}_f \quad (25)$$

$$\text{PEC}_{\text{ref}} = E_{\text{fac}} \text{PEC}_e + F_{\text{fac}} \text{PEC}_f \quad (26)$$

$$\text{CDE}_{\text{DCCHP}} = E_m \text{CDE}_e + F_m \text{CDE}_f \quad (27)$$

$$\text{CDE}_{\text{ref}} = E_{\text{fac}} \text{CDE}_e + F_{\text{fac}} \text{CDE}_f \quad (28)$$

where Cost_e , Cost_f , PEC_e , PEC_f , CDE_e , and CDE_f are the cost, PEC factors, and CDE factors for electricity and natural gas, respectively. The PEC factors represent the primary energy consumed to deliver a unit of electricity or fuel, CDE factors represent the CO₂ emissions associated with production of a unit of delivered electricity or natural gas fuel. The values used for each of these factors are included in the results section of this paper.

If carbon credits obtained for reduction of CDE are considered, then the CDE savings of a D-CCHP system over the reference case can be evaluated as

$$\Delta \text{CDE} = \text{CDE}_{\text{ref}} - \text{CDE}_{\text{DCCHP}} \quad (29)$$

and the reduced operating cost for the D-CCHP system is given by

$$OpCost_{DCHP}^{CC} = OpCost_{DCHP} - \Delta CDE \times CC \quad (30)$$

where CC is the rate of carbon credits in \$/t of CO_2 .

Operational cost savings, PEC savings, and CDE savings of the D-CCHP system are presented as percent variation with respect to the reference case and can be determined as

$$OpCost_{savings} = \frac{OpCost_{ref} - OpCost_{DCHP}}{OpCost_{ref}} \times 100 \quad (31)$$

$$PEC_{savings} = \frac{PEC_{ref} - PEC_{DCHP}}{PEC_{ref}} \times 100 \quad (32)$$

$$CDE_{savings} = \frac{\Delta CDE}{CDE_{ref}} \times 100 \quad (33)$$

Additional parameters are introduced in this paper to help analyze the performance of the D-CCHP system. R_{cool} gives the ratio of the cooling load to the overall thermal load, while R_{heat} gives the ratio of the building heating load to the overall thermal load. TD yields the thermal difference for the building, as shown in Eqs. (34)–(37) below.

$$R_{cool} = \frac{Q_{cool}}{Q_{thermal}} \quad (34)$$

$$R_{heat} = \frac{Q_b}{Q_{thermal}} \quad (35)$$

$$Q_{thermal} = Q_{cool} + Q_b \quad (36)$$

$$TD = R_{heat} - R_{cool} = \frac{Q_b - Q_{cool}}{Q_{thermal}} \quad (37)$$

3. Results and discussion

The building heating demand and the building electric demand are determined by running year-long EnergyPlus (U.S. Department of Energy, 2012) simulations for the selected building (full-service restaurant) in each of the nine U.S. locations examined: Seattle, WA; Phoenix, AZ; Minneapolis, MN; Helena, MT; Chicago, IL; Houston, TX; Baltimore, MD; San Francisco, CA; and Fairbanks, AK. These cities were selected since they represent the different climate zones in the United States. The D-CCHP system model described in Section 2 has been applied to a full-service restaurant building of 511 m². Hourly simulations were performed for the building in each location over the course of one year. The total building electric requirement (E_{fac}), electricity required for cooling (E_{cool}), and facility gas requirement (F_{fac}) over the year are given in Table 1. The D-CCHP system model was implemented on an hourly basis. All of the efficiency values used in this simulation are listed in Table 2 and are based on manufacturer data, on typical

efficiency values, and on previous optimization studies (ASHRAE Handbook, 2008; Cho et al., 2008; Fumo et al., 2008).

The cost of electricity and natural gas (Environmental Protection Agency and the US Department of Energy, 2013), PEC conversion factors (American Gas Association, 2013), and CDE conversion factors (U.S. Environmental Protection Agency, 2010) for each location are listed in Table 3, along with the corresponding spark spreads. The cost spark spread, SS_{cost} , is defined as the difference in electricity and fuel cost; the PEC spark spread, SS_{PEC} , as the difference in electricity and fuel PEC conversion factors, and the CDE spark spread, SS_{CDE} , as the difference in electricity and fuel CDE conversion factors (Smith et al., 2011a, 2011b).

The savings over the reference case of the D-CCHP system model is first illustrated in this paper. Table 4 shows the selected engine sizes of the D-CCHP configuration for the full-service restaurant in each location examined obtained applying the model described in Section 2. PGU sizes are determined by simulating a wide range of combinations for PGU1 and PGU2 to determine one of the combinations that yields the greatest operational cost savings, similar to the process presented by Knizley and Mago (2012a) for the D-CHP system evaluation.

3.1. Spark spread and potential savings in operating cost, PEC, and CDE using D-CCHP

Figs. 2–4 show the performance of a D-CCHP system with respect to the reference case (0% line) using the PGUs combinations presented in Table 4. Each location is investigated in terms of operational cost, PEC, and CDE, and the spark spreads for cost, PEC, and CDE are also presented in these figures. In each figure, the locations are presented from left to right in terms of increasing spark spread for the appropriate parameter (cost, PEC, or CDE).

Examining Fig. 2, it can be seen that a D-CCHP system performs well in terms of operating cost for all locations except Seattle and Phoenix, which have low cost spark spreads. This indicates that

Table 2
Efficiency parameters.

Symbol	Description	Value
η_{PGU1}	PGU1 efficiency	0.3
η_h	Efficiency of the building's heating system	0.8
COP_{vc}	COP for the building's vapor compression system	3
$\eta_{h,CCHP}$	Efficiency of the heating system used for D-CCHP	0.8
COP_{chill}	COP for the chiller used in D-CCHP configuration	0.8
η_{hrs}	Efficiency of heat recovery system	0.8
η_{boiler}	Boiler efficiency	0.8
ξ	PGU energy loss factor	0.95
a	PGU2 efficiency parameter (ASHRAE Handbook, 2008)	2.3698
b	PGU2 efficiency parameter (ASHRAE Handbook, 2008)	1.0322

Table 1
Specifications for the full-service restaurant in each location (U.S. Department of Energy, 2012).

City	Electric requirement for facility (SHP) (E_{fac}) (kW h/yr)	Electricity for cooling (SHP) (E_{cool}) (kW h/yr)	Gas requirement (SHP) (F_{fac}) (kW h/yr)
Seattle	298,559	3,950	472,575
Phoenix	362,410	63,356	313,121
Minneapolis	310,787	14,490	617,087
Helena	305,544	8,138	566,079
Chicago	314,713	18,113	544,085
Houston	358,799	59,479	332,573
Baltimore	321,022	23,859	477,706
San Francisco	297,252	2,800	392,165
Fairbanks	294,341	1,733	927,771

Table 3

Cost (Environmental Protection Agency and the US Department of Energy, 2013), PEC (American Gas Association, 2013), and CDE (U.S. Environmental Protection Agency, 2010) factors and spark spreads.

City	Cost _e \$/kW h	Cost _f \$/kW h	PEC _e	PEC _f	CDEF _e kg/kW h	CDEF _f kg/kW h	SS _{cost} \$/kW h	SS _{PEC}	SS _{CDE} kg/kW h
Seattle	0.068	0.041	1.81	1.09	0.163	0.1836	0.027	0.72	−0.021
Phoenix	0.085	0.041	3.06	1.09	0.553	0.1836	0.044	1.97	0.369
Minn.	0.075	0.031	3.53	1.09	0.72	0.1836	0.044	2.44	0.536
Helena	0.082	0.034	2.91	1.09	0.714	0.1836	0.048	1.82	0.530
Chicago	0.086	0.031	3.50	1.09	0.524	0.1836	0.055	2.41	0.340
Houston	0.102	0.031	3.16	1.09	0.668	0.1836	0.071	2.07	0.484
Baltimore	0.123	0.041	3.25	1.09	0.586	0.1836	0.082	2.16	0.402
San Fran.	0.119	0.031	2.45	1.09	0.318	0.1836	0.088	1.36	0.134
Fairbanks	0.147	0.031	2.90	1.09	0.502	0.1836	0.116	1.81	0.318

Table 4

Selected PGU sizes for D-CCHP configuration.

CITY	D-CCHP	
	PGU1	PGU2
Seattle	10	20
Phoenix	10	25
Minneapolis	10	30
Helena	8	30
Chicago	10	30
Houston	15	25
Baltimore	10	30
San Francisco	15	25
Fairbanks	10	35

the price of electricity is low relative to the price of fuel in these locations, so that on-site generation does not provide as much financial benefit. Phoenix also has a significant cooling load, almost as large as its heating load, and its atypical performance will be discussed in greater detail in the next section of this paper. Many CHP system strategies are unlikely to be beneficial in terms of cost for Seattle and Phoenix, since the cost spark spreads of these cities are relatively low. However, in the locations with higher cost spark spreads, the D-CCHP system performs well in terms of operating cost, with San Francisco and Fairbanks benefiting the most from the D-CCHP system configuration having savings of 32.5% and 31.1%, respectively, over the reference case.

Fig. 3 shows that PEC savings can be achieved for most of the locations shown. With the exception of Seattle, PEC savings from a D-CCHP system implementation are achievable when selecting PGU sizes based on operating cost. The generation profile for the region near Seattle is particularly efficient in delivering power with very low consumption of primary energy (American Gas Association, 2013). Seattle has a PEC spark spread of 0.72, while each of the other locations has a spark spread of 1.36 or higher. Chicago and Minneapolis, each with PEC spark spreads of about 2.4, benefit the most in terms of PEC from a D-CCHP configuration, with savings over the reference case of 20.6% and 19.6%, respectively.

Fig. 4 shows the CDE savings for the D-CCHP system in each location. The two locations with the lowest CDE spark spreads, Seattle and San Francisco, do not benefit in terms of CDE savings from the dual CCHP configuration. This is due to the relatively clean fuel mix used to generate power in these regions (American Gas Association, 2013). Helena and Minneapolis have the highest CDE spark spreads of about 0.5 and show CDE savings over the reference case of 29.5% and 28.4%, respectively. In general, it can be observed from Figs. 2–4 that higher spark spreads yield greater savings for a D-CCHP configuration.

3.2. Performance of D-CCHP compared to D-CHP

Spark spread has been shown to be a viable indicating parameter of the performance of a D-CCHP system; however, the comparative performance of a D-CCHP system to a D-CHP system is examined in this section. While spark spreads can indicate the feasibility of D-CCHP system implementation, they do not provide enough information to determine if D-CCHP systems perform better or worse than D-CHP systems in certain locations. In order to investigate the performance of D-CCHP systems versus D-CHP systems, the parameters R_{cool} , R_{heat} , and thermal difference, TD , defined in Eqs. (34)–(37) are introduced. Fig. 5a shows the distribution of R_{cool} and R_{heat} for each city, along with the operating cost savings of a D-CCHP system over a D-CHP system for each location. The D-CCHP system operating cost relative to the D-CHP system is calculated as shown in Eq. (38), and PEC and CDE savings relative to a D-CHP system are found in a similar manner.

$$OpCost_{savings,DCCHP/DCHP} = \frac{OpCost_{DCHP} - OpCost_{DCCHP}}{OpCost_{DCHP}} \quad (38)$$

In Fig. 5a, the locations where operational cost savings were determined to be possible for D-CCHP are presented from left to right in terms of decreasing the TD values (increasing cooling loads). The PGU sizes for the D-CHP configurations are determined by simulating different combinations of PGU1/PGU2 using the model presented by Knizley and Mago (2012a) to determine one of the combinations that yields the greatest operational cost savings. The results are presented in Table 5. The PGU sizes used for the D-CCHP simulation are the same as those listed in Table 4. Fig. 5a illustrates, for the locations where the D-CCHP system could produce cost savings, whether the D-CCHP system would provide cost savings relative to D-CHP system. In each of these seven cities, the D-CCHP system has the potential to provide greater operational cost savings than the D-CHP system, although the increase in several locations is very small. Notably, Minneapolis and Phoenix (not presented in Fig. 5a) have the same cost spark spread of \$0.044/kW h, but the D-CCHP system yields cost savings in Minneapolis and not in Phoenix. The TD values for Minneapolis and Phoenix can be used to explain this discrepancy. The TD values for Minneapolis and Phoenix are, respectively, 0.84 and 0.14. This indicates that, as expected based on their climate zones, Minneapolis requires a much greater fraction of its total thermal load in the form of heat, while Phoenix requires a significant fraction of its thermal load in the form of cooling. Minneapolis shows an operating cost savings increase of 0.15% from the D-CHP system to the D-CCHP system, while the operating cost savings for Phoenix decreases by 10% between the D-CHP system and the D-CCHP system.

In Fig. 5b, these additional savings percentages are presented against thermal difference (TD) for each location. In general, a

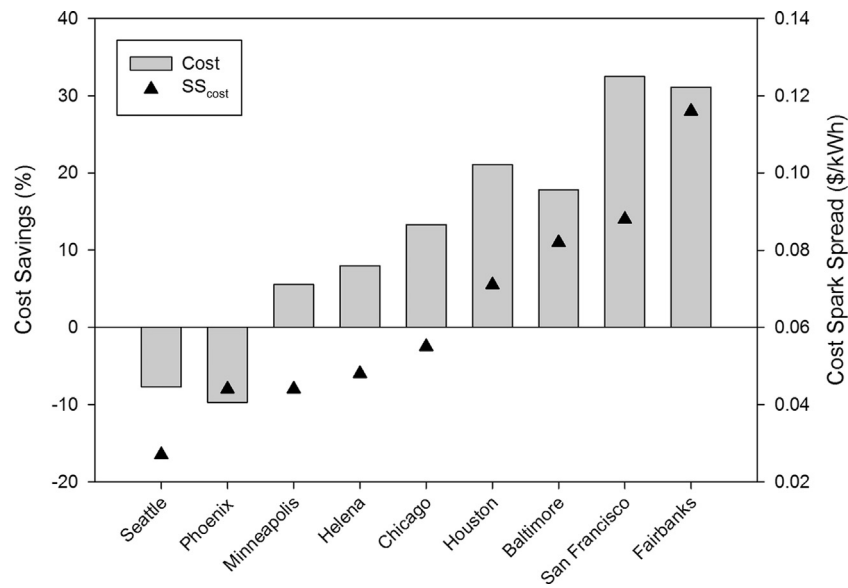


Fig. 2. Performance of D-CCHP over the reference case in terms of operating cost savings, ordered by cost spark spread.

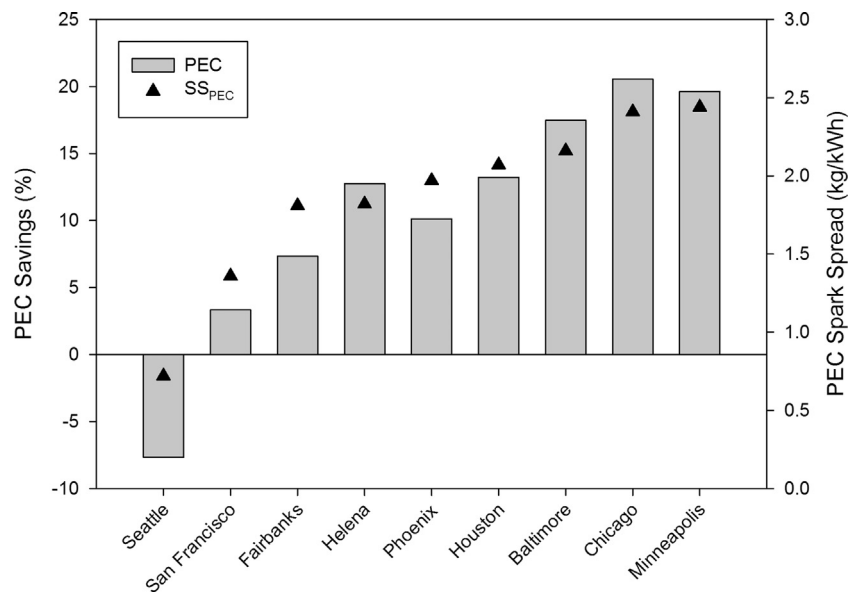


Fig. 3. Performance of D-CCHP over the reference case in terms of PEC savings, ordered by PEC spark spread.

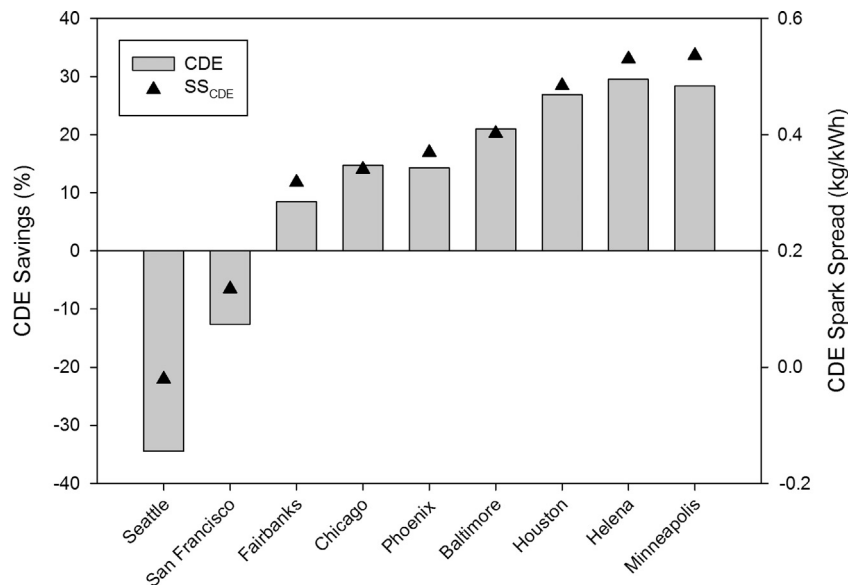


Fig. 4. Performance of D-CCHP over the reference case in terms of CDE savings, ordered by CDE spark spread.

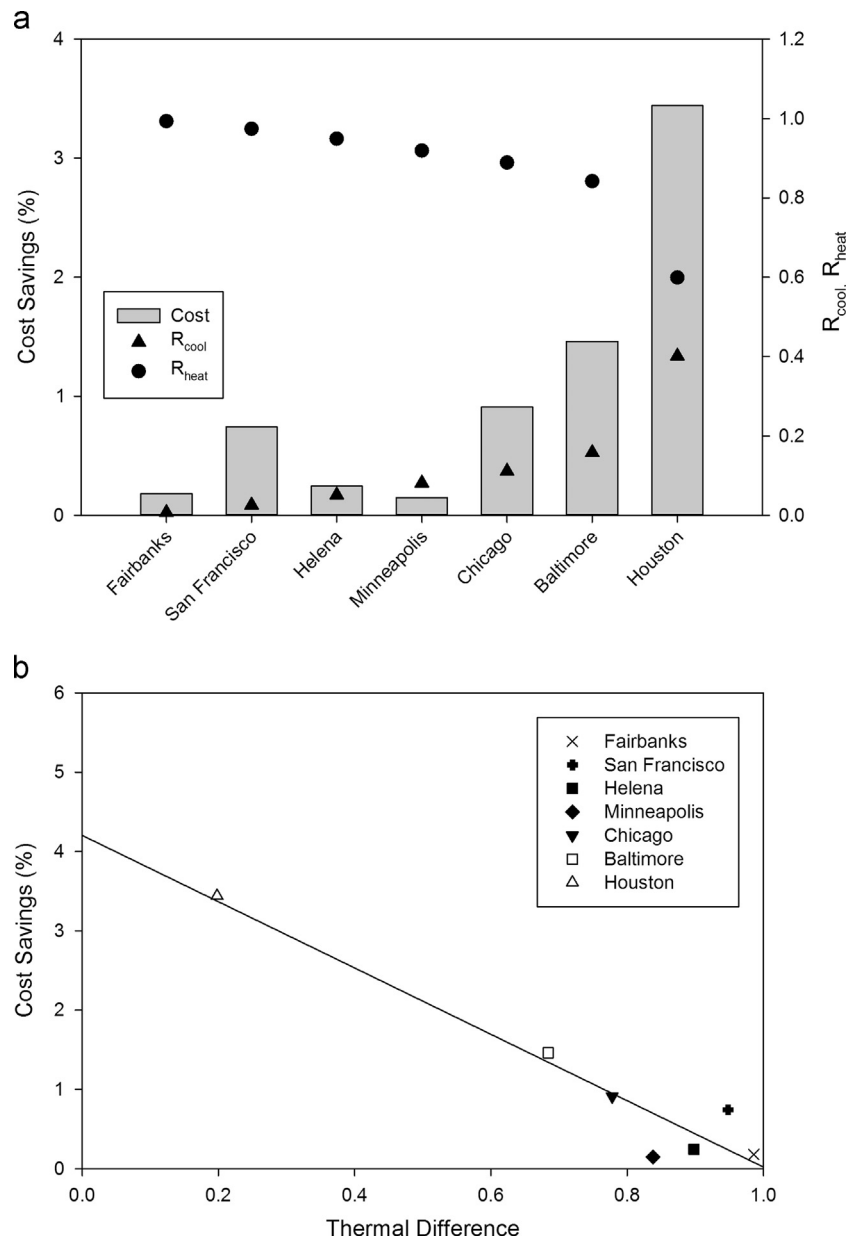


Fig. 5. (a) Operating cost savings of D-CCHP relative to D-CHP and thermal loads by city where cost savings are possible. (b) Operating cost savings of D-CCHP relative to D-CHP versus thermal difference.

Table 5

Selected PGU sizes for D-CHP configuration.

CITY	D-CHP	
	PGU1	PGU2
Seattle	10	20
Phoenix	15	5
Minneapolis	10	25
Helena	8	30
Chicago	8	30
Houston	15	20
Baltimore	10	30
San Francisco	15	25
Fairbanks	10	35

higher TD indicates that most of the thermal load is in the form of heat, and the D-CCHP system is less advantageous compared with the D-CHP system. This is reflected in the lower operational cost

savings percentages shown on the right side of the graph for Fairbanks, San Francisco, Helena, and Minneapolis. A least-squares linear approximation is shown as a dotted line. The cities which fall above this dotted line (San Francisco and Baltimore) have among the highest SS_{cost} values of the cities shown (see Table 3). Therefore, the cost savings are higher than what is indicated by the TD trendline because of the significant cost reduction occurring in these locations from the use of natural gas. The cities which fall below the line (Minneapolis and Helena) have SS_{cost} values below those of the other cities shown.

After examining the spark spreads to determine the D-CCHP system or the D-CHP system feasibility, the TD can be examined for locations where spark spread could not predict whether cost savings were possible. However, for those locations where the spark spread is sufficiently high to yield cost savings for most CHP configurations (above \$0.05/kW h for the building and cities analyzed in this paper), then a smaller TD can show a benefit of a D-CCHP system over a D-CHP system. Operating cost savings increases of a D-CCHP system

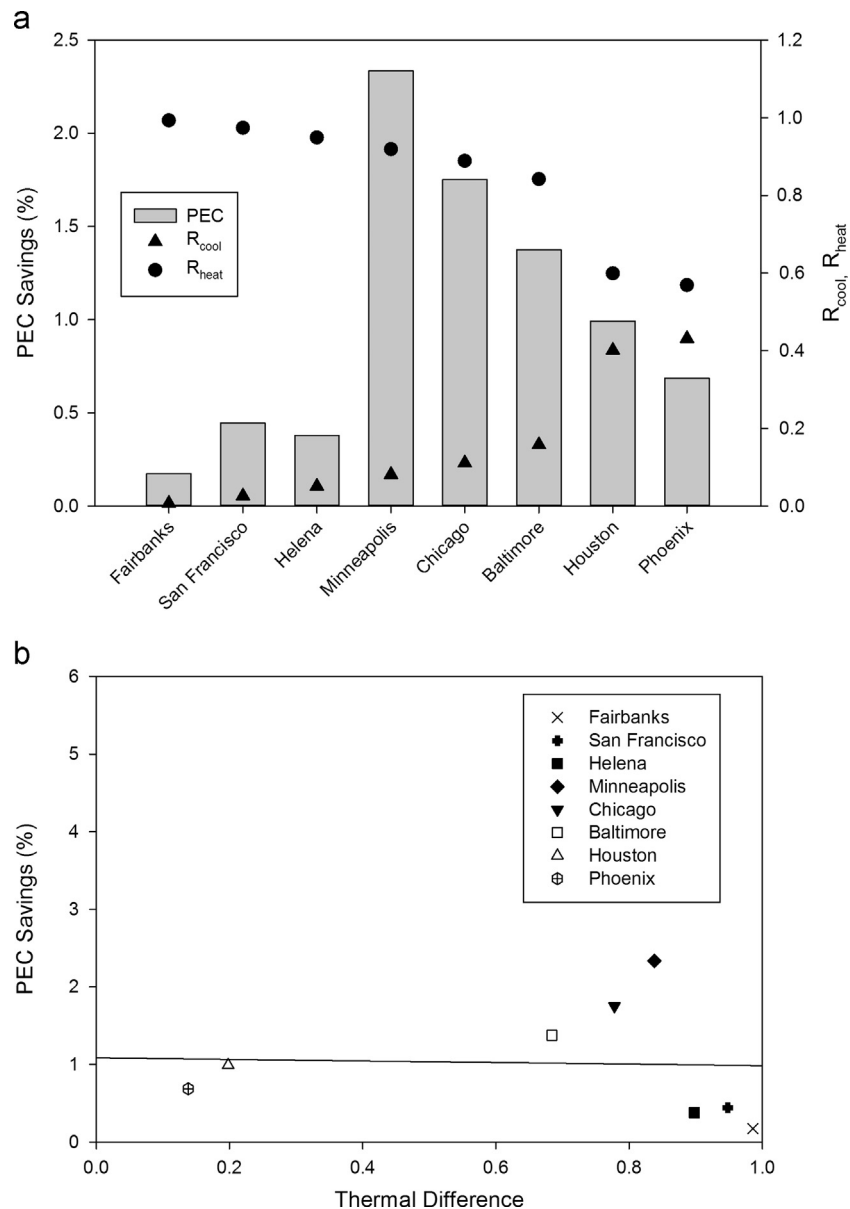


Fig. 6. (a) PEC savings of D-CCHP relative to D-CHP and thermal loads by city where PEC savings are possible. (b) PEC savings of D-CCHP relative to D-CHP versus thermal difference.

over a D-CHP system are greatest for Houston and Baltimore, with a 3.44% savings increase in Houston and 1.46% increase in Baltimore. Houston and Baltimore buildings have TD values of 0.2 and 0.68, respectively, with Houston's larger cooling demand leading to increased benefits from the use of D-CCHP systems rather than D-CHP systems. Fairbanks and San Francisco, two locations with very low cooling loads, have respective cost savings increases over D-CHP systems of 0.18% and 0.74%. The TD values are highest for those locations, with values of 0.99 and 0.95 in Fairbanks and San Francisco, respectively. Although SS_{cost} is highest for Fairbanks, using a D-CCHP system rather than a D-CHP system does not provide significant cost benefits because there is very little cooling load in this location, as indicated by its TD value of 0.99.

In Fig. 6a, the locations where PEC savings were determined to be possible for the D-CCHP system are presented from left to right in terms of decreasing TD values (increasing cooling loads). This illustrates, for these locations where PEC savings are possible, whether a D-CCHP system would provide PEC savings relative to a D-CHP system. In each of these eight cities, a D-CCHP system has

the potential to provide greater PEC savings than a D-CHP system, although the increase is minimal, less than 2% in each city except Minneapolis. The mid-range TD values (Minneapolis, Chicago, and Baltimore) yield the greatest savings of a D-CCHP system over a D-CHP system in terms of PEC, but the change from a D-CCHP system to a D-CHP system is small.

In Fig. 6b, these additional PEC savings percentages are presented against the TD values for each location. PEC savings from D-CCHP versus D-CHP configurations do not present a strong trend. However, the cities which provide above average PEC savings using a D-CCHP system rather than a D-CHP system are again the cities with the highest SS_{PEC} values: Baltimore, Chicago, Minneapolis; and the cities which provide the least PEC savings with a D-CCHP system rather than a D-CHP system are among the lowest SS_{PEC} values: Fairbanks, San Francisco, and Helena.

In Fig. 7a, the locations where CDE savings were determined to be possible for D-CCHP configurations are presented from left to right in terms of decreasing the TD values (increasing cooling loads). This illustrates, for these locations where CDE savings are possible, whether

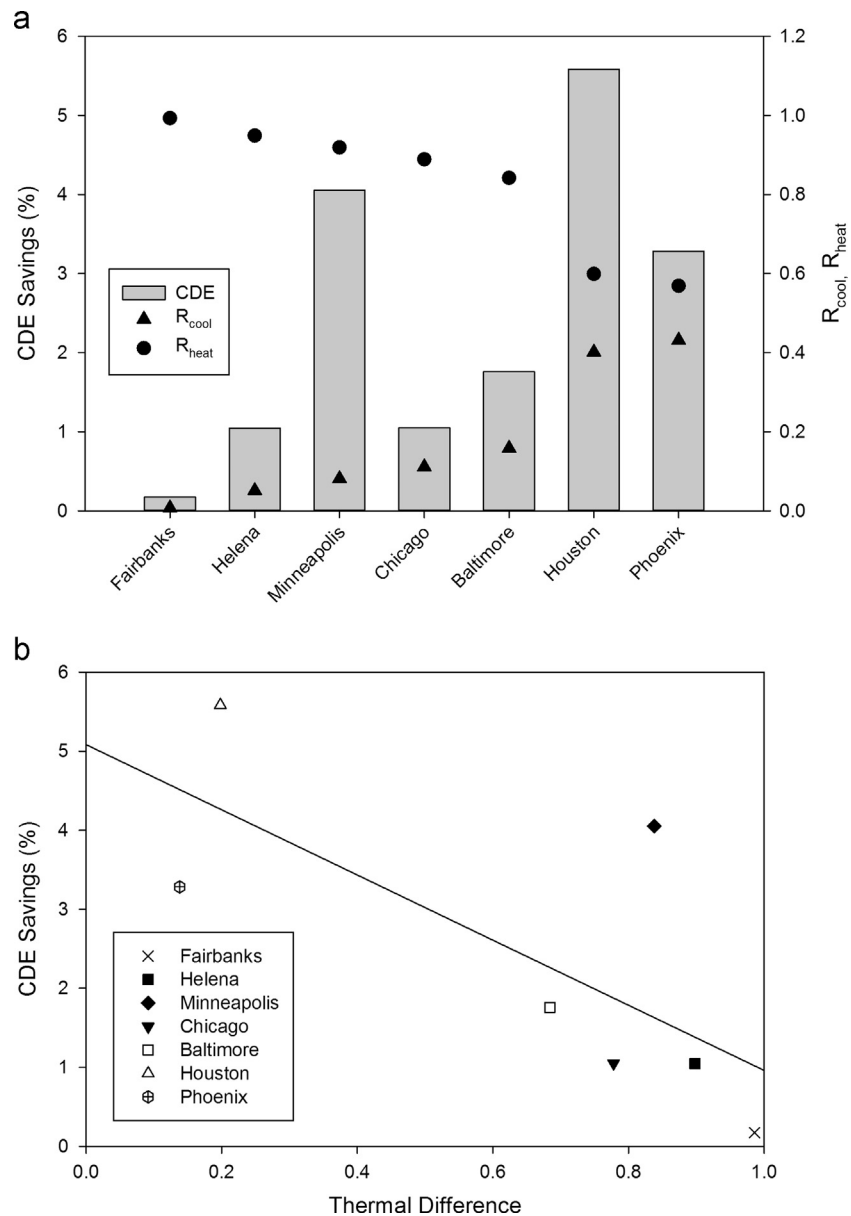


Fig. 7. (a) CDE savings of D-CCHP relative to D-CHP and thermal loads by city where CDE savings are possible. (b) CDE savings of D-CCHP relative to D-CHP versus thermal difference.

a D-CCHP system would provide CDE savings relative to a D-CHP system. In each of these seven cities, the D-CCHP configuration has the potential to provide greater CDE savings than the D-CHP configuration, with a significant increase in Houston.

In Fig. 7b, these additional CDE savings percentages are presented against the TD values spread for each location. CDE savings from a D-CCHP system versus a D-CHP system do not adhere to a strict trendline ($R^2=0.52$), but the general pattern is similar to that of cost savings shown in Fig. 5a. Both Houston and Minneapolis provide greater CDE savings than the general trend would indicate, and both cities are among the highest SS_{CDE} values. Phoenix and Fairbanks fall well below the trendline, and they have the lowest SS_{CDE} values of the cities shown.

3.3. Carbon credits and potential savings in operating cost using D-CCHP

As shown before, the D-CCHP system has the potential to reduce the CDE for most locations. For those locations where the

D-CCHP system is not able to reduce the operational cost, the use of carbon credits, if available, can be used to make the system more feasible from the operational cost perspective. In this section, the effect of carbon credits on operating cost savings with respect to the reference case is examined for the cases of Chicago and Phoenix. Chicago is chosen because it shows the median operating cost savings for the cities examined, and Phoenix is chosen to examine the effects of increased cost benefits with carbon credits because a D-CCHP configuration has a greater operating cost than the reference case in that location. Fig. 8 shows the new D-CCHP operational cost (Eq. (30)) versus the carbon credit for the city of Chicago. The carbon credit was varied from 0 to \$30/t. As expected, increasing the carbon credit decreases the new operating cost of the D-DCHP system and therefore increases the operating cost savings. Fig. 9 shows the new D-CCHP operational cost (Eq. (30)) versus the carbon credit for the city of Phoenix. Similar to Fig. 8, the carbon credit was varied from 0 to \$30/t. Fig. 9 shows that even if carbon credits were to reach \$30/t, the D-CCHP system would still not produce

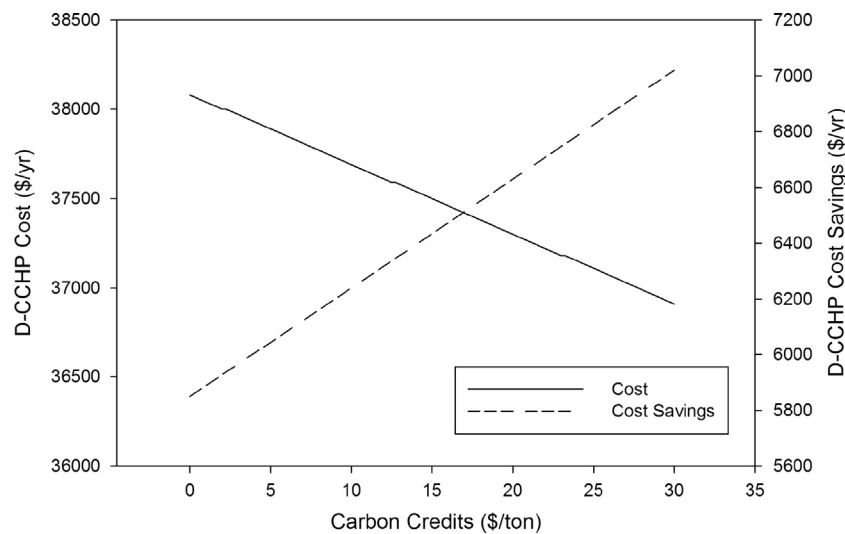


Fig. 8. Addition of carbon credits to operating cost and operating cost savings over reference case for full-service restaurant in Chicago, IL.

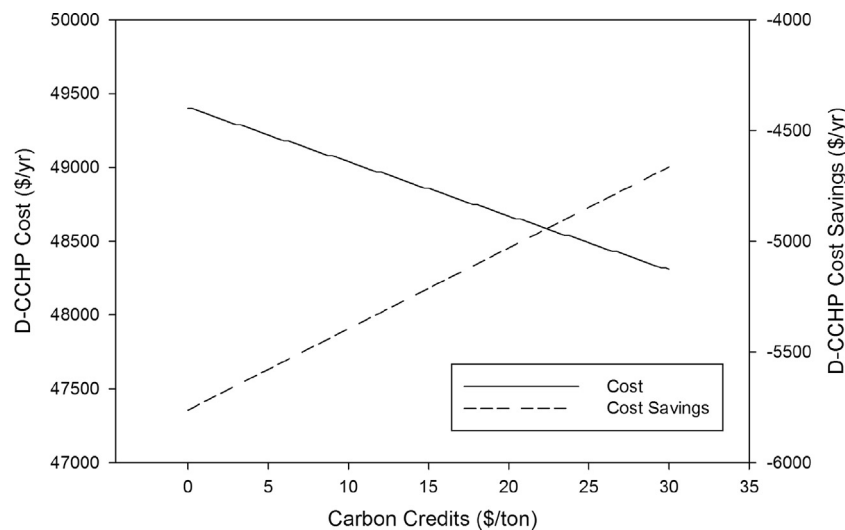


Fig. 9. Addition of carbon credits to operating cost and operating cost savings over reference case for full-service restaurant in Phoenix, AZ.

cost savings over the reference case for Phoenix, AZ. Since the values of carbon credits are different for different locations, it has to be analyzed for each case to determine if they might or might not have an impact on the operational cost savings of the D-CCHP system implementation.

4. Conclusions and policy implications

In this paper, a model to evaluate the performance of a D-CCHP system with two PGUs operating simultaneously using differing strategies was proposed. This system has been compared on the bases of operating cost, PEC, and CDE to a reference case in which a SHP system is employed. The D-CCHP system performance was shown to correlate well with cost spark spread, primary energy spark spread, and carbon dioxide emissions spark spread, with higher spark spreads generally signifying greater savings. The D-CCHP system is able to reduce the operational cost with respect to the reference case for all locations except Seattle and Phoenix, which have low SS_{cost} . With the exception of Seattle, which has low SS_{PEC} , the D-CCHP system implementations can yield PEC savings. On the other hand, the D-CCHP system is able to reduce the CDE with respect to

the reference case for all locations except for Seattle and San Francisco (cities with low SS_{CDE}).

For those locations that show D-CCHP savings over the reference case, the D-CCHP system performance was also compared to the D-CHP performance. It was found that, in general, D-CCHP system performs comparably to the D-CHP system, but the D-CCHP configuration performs slightly better for locations where D-CCHP savings can be achieved. The TD parameter was introduced to explain the variations in the relative savings of the D-CCHP system over the D-CHP system. Results indicated that, for locations where D-CCHP configurations can yield savings, lower TD tend to yield higher savings. Exceptions to this trend can be attributed to very high or very low spark spreads. In terms of operational cost savings, Baltimore and Houston show the greatest savings for a D-CCHP system over a D-CHP system, and those locations have the lowest TD . San Francisco yields higher operational cost savings for D-CCHP systems with respect to D-CHP system than would be expected from its relatively high thermal difference, but this discrepancy is explained by the high cost spark spread of San Francisco. In terms of PEC savings, most of the locations show comparable savings for D-CCHP systems relative to D-CHP systems. For the locations that perform better than average for D-CCHP savings with respect to the D-CHP configuration, high PEC

spark spreads are present. CDE savings tend to decrease with increasing TD , with exceptions of Houston and Minneapolis having higher than expected, with regard to TD , CDE savings of D-CCHP relative to D-CHP. In addition to having a low TD , Houston also exhibits a high CDE spark spread that can account for the higher than expected savings. Minneapolis has the highest SS_{CDE} , which also accounts for its higher than expected CDE savings.

The effect of carbon credits on operational cost savings was also examined. Increasing the value of carbon credits will also increase the operational cost savings for locations that have CDE savings when employing a D-CCHP configuration. However, as shown for the case of Phoenix, carbon credits alone may not be able to overcome operational cost increases from D-CCHP for a location with a low spark spread and low TD value. It is important to highlight here that, with the operational cost savings obtained from the D-CCHP system operation presented in this paper, a complete economic calculation could be performed. Using the cost savings per year and the yearly electric and natural gas consumption, and the cost of electricity and natural gas, the corresponding dollar amount for the yearly savings can be determined. With this information, the payback period can be obtained once the cost of the equipment, installation, depreciation rate, and tax incentives are determined. Alternatively, this capital cost could be integrated into the daily operating cost values using the methodology presented by Fang et al. (2012a, 2012b).

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